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ABSTRACT

The cyclotron harmonic plasma resonances observed by Alouette II were investigated using a technique that yielded frequency measurements with an accuracy of the order of 1 kc/s. The resonances observed near f_H and $2f_H$ experience frequency shifts of the order of +2% and +0.5%, respectively, when $f_N/f_H \approx 3$ where f_N is the electron plasma frequency and f_H is the electron cyclotron frequency. The resonances observed above f_T approach the true frequency values of nf_H as n increases; beyond about n=5 the observed cyclotron harmonic resonant frequencies are consistent with a single value of f_H which agrees with model magnetic field calculations within the estimated 0.2% reliability of this field. The frequency shifts observed previously for these resonances on the Alouette I data are attributed to magnetic contamination from the Alouette I spring steel antennas. A comparison of the earlier Alouette I results with the present Alouette II results indicates that the bulk of the original excitation volume associated with the higher cyclotron harmonic resonances is confined to a region considerably less than one antenna length in radius from the antenna, that the size of this region decreases with increasing harmonic number n, and that it increases significantly as the radiating antenna becomes parallel to the direction of the earth's magnetic field.

INTRODUCTION

The plasma resonances observed on the Alouette I and II topside sounders have been attributed to the reception of plasma waves of low group velocity that are excited by the sounder pulse[1]. Investigations of the electron cyclotron harmonic resonances can provide pertinent information in (a) the plasma wave dispersion theory associated with these resonances, (b) the problem of determining the interaction of a spacecraft with the ambient ionospheric plasma, and (c) the possible application of resonance observations to magnetic field measurements. The main problem in these investigations is that the exact value of the earth's magnetic field $\vec{B}$ is not known at the position of the satellite. In addition, the receiver (in the case of Alouette I) was designed primarily for receiving the anticipated long range ionospheric echoes; thus it did not provide high resolution frequency information which is desirable for the investigation of the cyclotron harmonic plasma resonances. These resonances, which were not anticipated, have become an exciting "fringe benefit" of the topside sounder program.

The above problems were overcome in a previous analysis[2] of Alouette I data where frequency deviations (from a true harmonic relationship) of a few tenths of one percent were observed by: (1) selecting the data in a manner that insured a reliable reference level for the magnetic field, (2) determining a time duration vs. frequency curve for each resonance from the expanded sounder-receiver amplitude vs. time format, and (3) averaging the data from many ionograms for each resonance. Two types of deviations were observed. First, the value of f_H as determined by f_n/n decreased with increasing harmonic number n (when $n \geq 4$) to values lower than those expected from model magnetic field calculations (f_H is the electron cyclotron frequency and f_n is the frequency of the resonance observed near nf_H). The possibility that this

negative frequency shift, which is not predicted by any of the existing theoretical treatments of the problem, was due to magnetic contamination from the spring steel antenna elements used on Alouette I could not be entirely ruled out. Second, the frequencies of the resonances near $2f_H$ and $3f_H$ varied with the local electron density when these resonant frequencies were favorably located with respect to the upper hybrid frequency f_T.

This paper presents the results of an analysis of Alouette II data which was conducted to investigate the first of the above mentioned observed deviations. The main significance of using Alouette II data to investigate this frequency shift with harmonic number is that non-magnetic Be-Cu antennas were used on this satellite.

There are several differences between the present Alouette II study and the previous Alouette I study. First, the data were selected strictly on the basis of the quality and number of cyclotron harmonic resonances observed in the expanded frequency region below 2 Mc/s, whereas in the Alouette I analysis the data were selected without regard to the quality or number of resonances present - the main concern was to obtain reliable data samples in which the variations of critical parameters was restricted. Second, the increased frequency resolution on Alouette II (below 2 Mc/s) assisted in the identification of the resonant center frequency in that the nulls in the frequency spectrum of the sounder pulse could often be identified on the received resonant signal. Third, in order to make the identification of these nulls more definite, the strength of the resonant response to each sounder pulse was determined by recording the sounder receiver video amplitude output on fast moving (1800 in/min) film and measuring the area under the receiver amplitude trace as well as the time durations of the resonant responses (only the time durations were scaled in the Alouette I analysis).

Fourth, because of the increased frequency resolution on Alouette II, frequency deviations in the cyclotron harmonic resonances from the exact nf_H values could be detected on individual ionograms as well as on averaged data.

METHOD OF ANALYSIS

Ionograms were selected from the region where the earth's magnetic field $\vec{B}$ is a minimum along the Alouette II orbit, i.e., near apogee over South America, in order to obtain the maximum number of cyclotron harmonic resonances in the high resolution portion of the ionogram below 2.0 Mc/s. In many cases, resonances up to $8f_H$ were observed in the high resolution frequency range. Resonances observed above 2.0 Mc/s, where the frequency resolution is low, were not considered in this analysis (see Fig. 1).

The fine structure often observed on the Alouette II resonances is illustrated in Fig. 2. The resonance at $2f_H$ clearly reveals a pattern which is caused by the frequency spectrum of the transmitted sounder pulse. In order to illustrate why this pattern can be seen on the received signal, consider the ideal situation represented by Fig. 3. Here the frequency spectra of eight successive sounder pulses are shown as the sounder sweeps through a natural resonant frequency f_{res} of the medium which is indicated by the vertical dashed line. The spectrum labeled 1 at the top of the figure corresponds to a sounder pulse at a frequency 14 kc/s below f_{res}. A significant amount of energy is transmitted at f_{res}, however, which initiates a plasma wave at this frequency. The wide bandwidth of the receiver permits the reception of this plasma wave energy at the frequency of the transmitted pulse. The receiver's 3db points are indicated by short vertical lines at +8.5 kc/s and -28.5 kc/s on each spectrum; the corresponding 20db points are located at +26.5 kc/s and -46.5 kc/s. The receiver center frequency is offset by -10 kc/s with respect to the transmitter frequency[3] in order to optimize

the receiver response for the long range ionospheric echoes at frequencies above 2.0 Mc/s; at frequencies below 2.0 Mc/s it causes a skewing of the resonances. The receiver response to the resonant signals produced by the pulse sequence of Fig. 3 is sketched in the ionogram format in the upper right hand side of the figure.

The center frequency of each cyclotron harmonic plasma resonance was determined from a plot of the relative resonant strengths vs. the transmitted pulse frequencies of the individual pulses making up the resonance. A clear plastic overlay containing the frequency spectrum of the transmitted pulse was used to match the weak signals to the nulls and the strong signals to the peaks of the spectrum. The shift in the center frequency of the receiver was also a prime factor in determining the resonant center frequency, especially when this frequency was above f_T and when a Bernstein mode resonance[4] was prominent enough to degrade the spectral pattern of the cyclotron harmonic resonance. During reception of a strong resonance, such as the one observed near $2f_H$ in Fig. 2, the reaction of the automatic gain control (AGC) of the Alouette II receiver to the strong pulses leading up to the center frequency can more than compensate for the increased receiver sensitivity expected from bandwidth considerations for the pulses following the center frequency. When even stronger resonances are recorded, the AGC reaction can be so large that the receiver response to signals initiated by the peak in the frequency spectrum of the transmitted pulse at -10 kc/s is considerably stronger than the response to the center frequency peak. The observation of the spectral pattern of the transmitted sounder pulse on the received resonant signal, however, indicates that this AGC action did not prevent detection of the relative minima in the received energy. Using this technique the resonant center frequency could be determined within 0.7 kc/s to 2.5 kc/s depending on the character of the observed resonance profile.

Once the center frequency f_n was obtained for each cyclotron harmonic resonance the corresponding value for the magnetic field B_R was obtained by assuming $f_H = f_n/n$; B_R was then compared with the computed field B_c based on the GSFC

POGO (3/68) reference field[5] in a manner similar to that used in the earlier Alouette I analysis[2].

OBSERVATIONS

The difference field B_R-B_c vs. harmonic number n is presented in Fig. 4 for two ionograms from different passes (a and b), for 5 ionograms from a third pass (c), and for 4 ionograms from a fourth pass (d). The significant features of Fig. 4 are the following: (1) the observed frequency of the resonance near f_H is about 2% greater that the true value of f_H, e.g., in (a) it is high by 2.6%$\pm$0.5%, (2) the observed frequency of the resonance near $2f_H$ is about 0.5% greater than the true value of $2f_H$, e.g., the maximum frequency deviation is +0.8%$\pm$0.2% in (a), (3) no entry is present corresponding to n=3 because accurate frequency measurements were prevented by the overlapping of the resonance near $3f_H$ with the plasma resonance at f_N, and (4) the frequencies of the cyclotron harmonic resonances with n $\geq$ 4 decrease with increasing n until they level off in agreement with the true values of nf_H (the maximum frequency deviation when n=4 is +0.6% $\pm$ 0.1% in (a)). The "true values" referred to above are taken from a horizontal line passing through the higher harmonics. In each case this line is consistent with the B_R-B_c=0 level, since the standard error estimates[6] associated with the computed reference field B_c are about 15γ and the absolute level for the equatorial D_{st} (the average magnetic storm field over all longitudes) corrections[7] - which were applied to B_c in the present analysis - is uncertain by about 5 or 10γ. Several ionograms containing resonances as high as 14 f_H were investigated and again the higher harmonics were consistent with each other. A frequency shift as high as 0.5%, as observed on Alouette I[2], would have been detected in spite of the low frequency resolution between 2.0 and 8.5 Mc/s on Alouette II (Fig. 1).

The data represented in Fig.4 were recorded during very similar conditions in that f_N/f_H ranged only from 2.9 to 3.1 among the 11 ionograms. The clear observations of frequency shifts on individual ionograms in a and b, and the good agreement with the averaged results in c and d, is encouraging in view of the lengthy process required to make the analog to digital data conversion for precision frequency measurements. Also, this resolution permits frequency variations of individual cyclotron harmonic resonances to be investigated as f_N/f_H varies from ionogram to ionogram on a given pass.

DISCUSSION

The present observations indicate that when $f_n > f_T$, $f_n \rightarrow nf_H$ as n increases. This result indicates that the large negative frequency deviations observed for the higher harmonics on Alouette I were caused by magnetic contamination from its spring steel antennas. Several conclusions concerning the size of the original region of resonant excitation associated with these Alouette I resonances can now be made based on magnetic measurements of the same stock material used in the Alouette I antennas[2]: (1) the excitation region is not confined to the sheath region surrounding the antennas[2], (2) the bulk of the excitation volume is confined to a region considerably less than one antenna length in radius from the antenna, (3) the radius of this region decreases with increasing harmonic number n, and (4) it increases significantly, but is still less than an antenna length, as the radiating antenna element becomes parallel to $\vec{B}$. The last point is consistent with the observation[8] that the higher harmonic resonances are observed only when the radiating antenna is within about 15^{o} of being parallel to $\vec{B}$ and with the observations[2] suggesting that these resonances are observed only during the time interval required for the antenna to escape the region of original excition. The above comments concerning the excitation region

of the higher harmonic resonances observed by Alouette I should also hold for Alouette II since the method of excitation is similar. It is difficult to estimate the size of the resonant excitation region associated with the other plasma resonances observed on Alouette I and II until plasma wave dispersion effects can be separated from magnetic contamination effects; such an investigation is in progress.

The observations also indicate that the ambient magnetic field can be determined to an accuracy of 0.2% from frequency measurements of cyclotron harmonic resonances observed on individual Alouette II ionograms when these resonant frequencies f_n occur above f_T (approximately $f_n \geq f_T+3f_H$) and below 2.0 Mc/s. Such magnetic field measurements, however, may be more practical for investigating special events such as magnetic storms comparing results with other data of special interest, etc., rather than for magnetic survey investigations due to the lengthy data reduction procedure.

The large deviations from the zero level observed for the resonances below f_T, i.e., f_H and $2f_H$ in Fig. 4, and the smaller deviations observed for the resonances adjacent to f_T on the high frequency side, are believed to be closely related to the dispersion curves for the plasma waves attributed to these resonances and will be the subject of a separate paper. The relatively large scaling uncertainties for $4f_H$ in Fig. 4a and b and the correspondingly large standard deviations in c and d are attributed to the possible presence of a Bernstein mode resonance[4].

ACKNOWLEDGEMENT

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FIGURE CAPTIONS

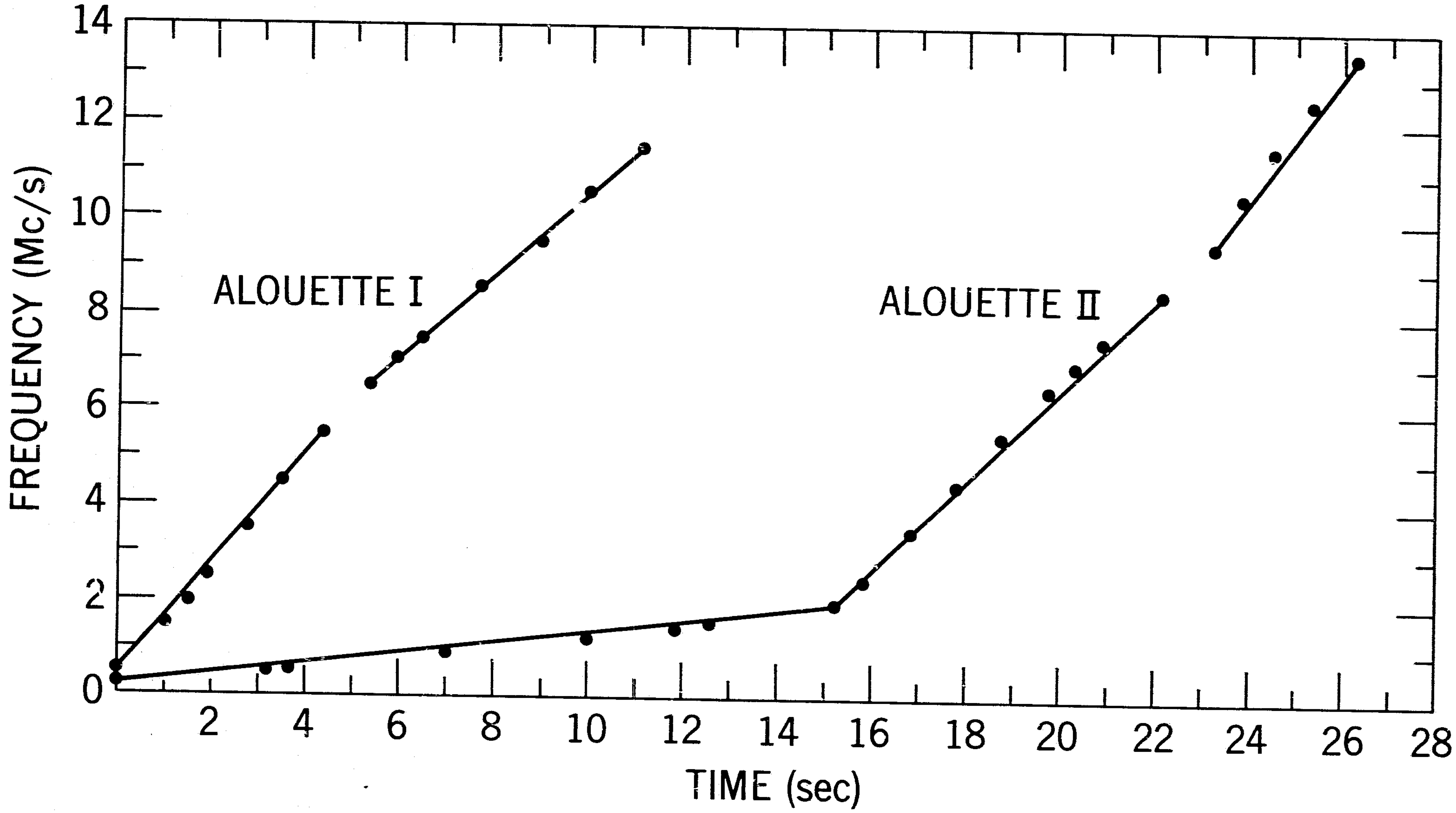
1. Frequency marks vs. time on Alouette I (BPO pass 1309, 3 Jan. 1963, 03:47:25 UT) and Alouette II (SNT pass 3184, 24 Aug. 1966, 19:06:58 UT). Straight lines connect the end points where noticeable breaks in the frequency sweep rate occur. In the frequency range above 2.0 Mc/s the frequency sweep rates for Alouette I and II are approximately the same but the frequency resolution of Alouette II is only one half that of Alouette I because the pulse repetition rate is one half the rate used on Alouette I.

2. An Alouette II ionogram (SNT pass 1537, 7 April 1966, 21:38:19 UT) which illustrates the detection of the spectral pattern of the transmitted sounder pulse on the received resonant signal at $2f_H$. The occurrence of more than one deep null on a given plasma resonance is not common because it requires the proper frequency sweep rate and the chance pulse transmission at a frequency which will produce a null in the transmitted energy at f_{res} (see Fig. 3). The above $2f_H$ resonance is a better than average example of this condition, whereas the corresponding f_H resonance is worse than average.

3. Frequency spectra of 8 successive sounder pulses near a natural resonant frequency f_{res} of the medium and the corresponding receiver response sketched in the ionogram format. The responses to pulses 2 and 7 are minimal because no energy is transmitted at f_{res} by the corresponding pulse spectra. The response to pulse 8 is larger than that of pulse 1 because f_{res} was near the center of the receiver bandwidth in the former case. (The effect of the automatic gain control (AGC) of the receiver, which would reduce the apparent received strength of pulse 8 relative to pulse 1, was ignored in this idealized example.)

FIGURE CAPTIONS CONTINUED

4. The difference field vs. harmonic number n for (a) QUI pass 5454, 4 March 1967, 06:16:31 UT and (b) QUI pass 5478, 6 March 1967, 06:49:31 UT; the points are centered on the error bars which represent estimates of the scaling uncertainty. The average difference field vs. n for (c) 5 ionograms from QUI pass 5466, 5 March 1967, 06:31:46 to 06:33:53 UT and (d) 4 ionograms from QUI pass 5537, 11 March 1967, 06:12:50 to 06:14:27 UT; the error bars represent $\pm\sigma/N^{\frac{1}{2}}$ where σ is the standard deviation of the observations and N is the number of observations. In (c) N=5 for all resonances except for $8f_H$ where N=4; in (d) N=4 for all resonances except for $8f_H$ where N=2. No entries were made for n=3 (see text). In all cases the satellite altitude was between 2930 and 2990 km and the true value of f_H was between .245 and .251 Mc/s; the Kp index was 1 for (d) and 2 for (a), (b), and (c).



FREQUENCY (Mc/s)
14
12
10
8
6
4
2
0
ALOUETTE I
ALOUETTE II
2
4
6
8
10
12
14
16
18
20
22
24
26
28
TIME (sec)

Figure 1

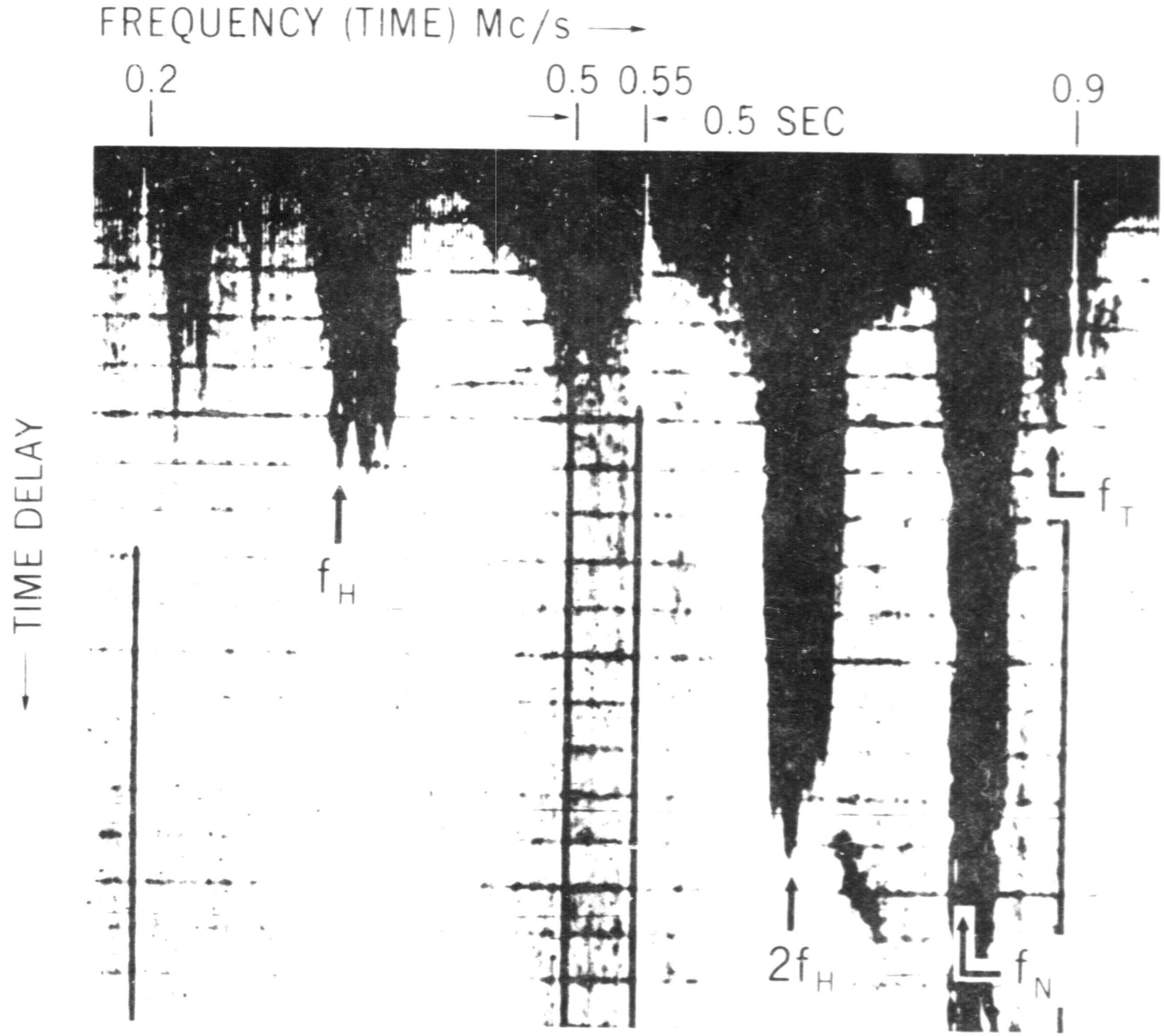


Figure 2

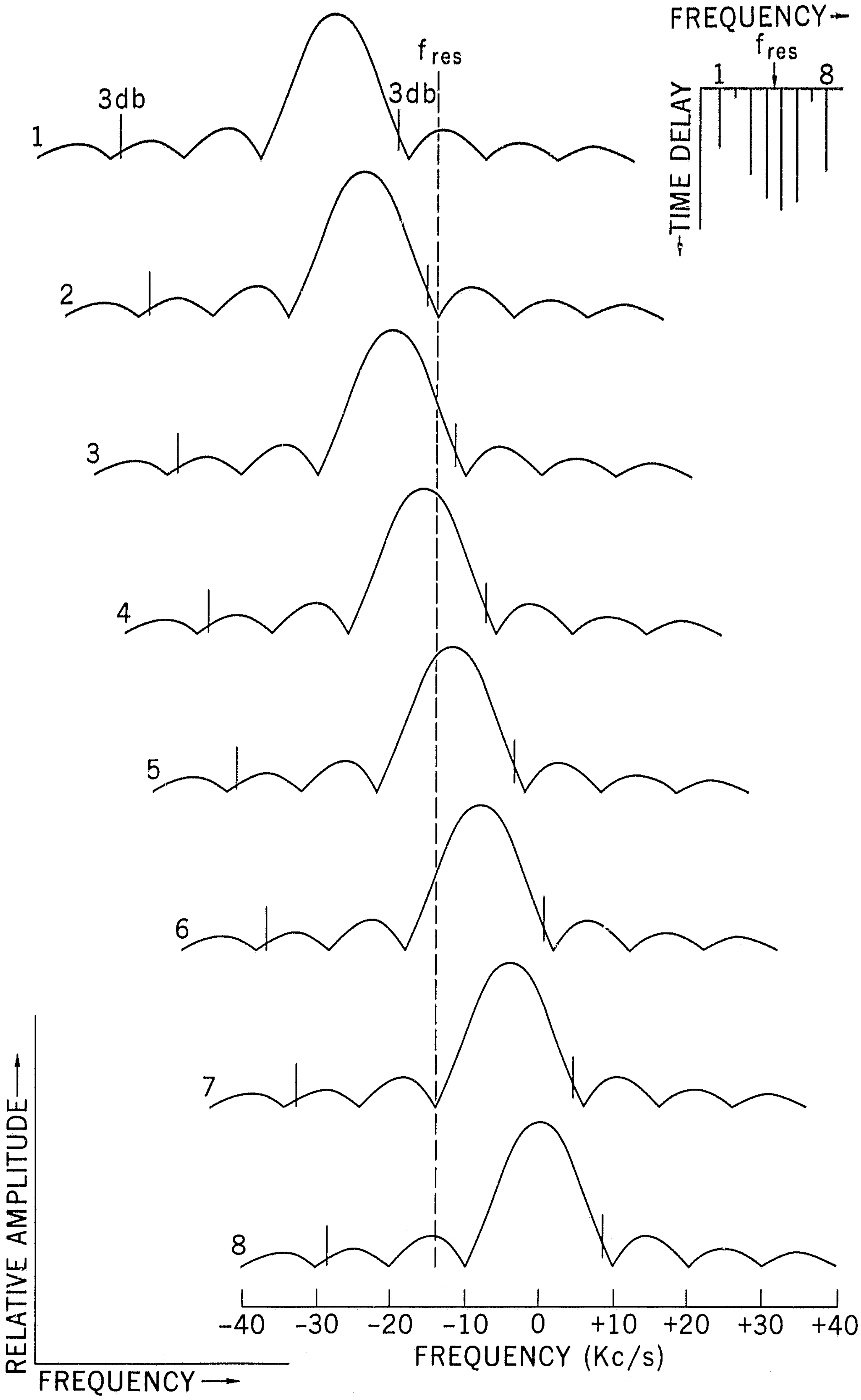
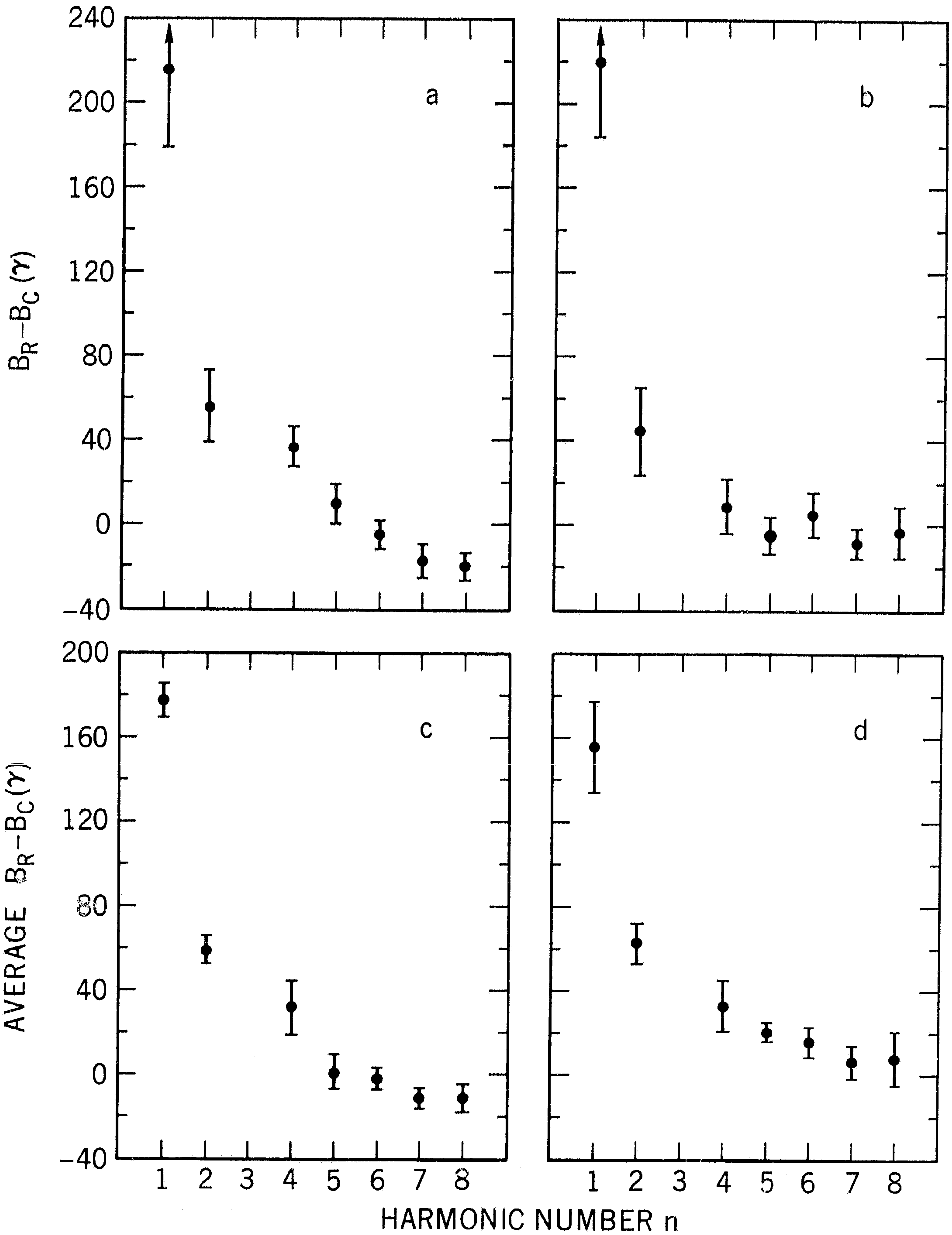

FREQUENCY
f_{res}
1
8
TIME DELAY
3db
3db
1
2
3
4
5
6
7
8
-40
-30
-20
-10
0
+10
+20
+30
+40
FREQUENCY (Kc/s)
RELATIVE AMPLITUDE
FREQUENCY

Figure 3



240
200
160
120
80
40
0
−40
a
b
c
d
$B_R - B_C (\gamma)$
200
AVERAGE $B_R - B_C (\gamma)$
1 2 3 4 5 6 7 8
HARMONIC NUMBER n

Figure 4